2. The SDMA Concept

Wireless communication systems are generally composed of one or more local central sites, herein termed *base stations*, through which wireless transmitter/receivers gain access to a larger information network. Base stations service *local* areas wherein a number of wireless users, fixed or mobile, are located. The function of the base station is to relay messages to and from users all over the network. In cellular mobile systems, for example, this task is performed by relaying messages to and receiving signals from a Mobile Telephone Switching Office (MTSO). A wireless user establishes a two-way (full-duplex) communication link with one or more other users also having some access to the network by first requesting access to the network through the local base station. This communication is accomplished in cellular mobile communications and wireless local area computer networks (LANs), for example, by suitably modulating electromagnetic waves. The same is true of the next generation Personal Communication Systems (PCSs) to which this document is directed.

Current state-of-the-art requires that users transmit signals in different frequency channels, use different coding schemes in the same frequency channels, or be transmitted in non-overlapping time intervals for the signals to be correctly received. SDMA is a new technique for separating multiple messages in the same frequency, code, or time channel using the fact that they are in different *spatial* channels. Hereinafter, the term *channel* will be used to denote any of the conventional channels (frequency, time, code) or any combination thereof. The term *spatial channel* refers to the new concept unique to SDMA.

Wireless communication is becoming an increasingly common form of communication, and the demand for such service continues to grow. Examples in operation today include cellular mobile communication networks, wireless telephone networks, cordless telephones, satellite communication networks, wireless cable TV, multi-user paging systems, high-frequency (HF) modems, and more. The next generation PCS systems will be yet another addition to this list. Current implementations of these communication systems are all confined to limited frequency bands of operation either by practical considerations or, as is more often the case, by government regulation. As the capacity of these systems has been reached, demand for more service has had to be met by allocating more frequency spectrum to the particular application along with attempts to utilize the allocated spectrum more efficiently. In light of the basic physical principle that transmission of information requires bandwidth, the fundamental limitations of a finite amount of practically usable spectrum present a substantial barrier to meeting an exponentially increasing demand for wireless information transmission. Since, as has been demonstrated over the last decade, the amount of practically usable frequency spectrum can not keep pace with the demand, there is a critical need for new technology for increasing the ability of such systems to transfer information. This document directly addresses this need and describes proprietary Spatial Communications, Inc. technology which is compatible with current as well as future modulation schemes and standards.

2.1 Review of Current Technology

In current state-of-the-art, a base station serves many channels by means of different multiple access schemes, the most common being Frequency-Division Multiple Access (FDMA), Time-Division Multiple Access (TDMA), and more recently Code-Division Multiple Access (CDMA). All current systems employ FDMA wherein the available frequency bandwidth is sliced into multiple frequency channels and signals are transmitted simultaneously, with a maximum of one per channel at any given time. All wireless systems also currently employ a form of TDMA, a technique wherein multiple users share a common frequency channel by doing so at different times, in that when a user no longer requires the channel assigned to it, the channel is reassigned to another user.

2.1.1 TDMA

In the more common meaning of the term, TDMA is also being exploited on a more fine grain level, an example of which is the implementation of the IS-54 domestic digital cellular system (D. Goodman, "Trends in Cellular and Cordless Communications," *IEEE Communications Magazine*, June 1991). Analog data, such as voice, is digitized, compressed, then sent in bursts over an assigned frequency channel in assigned *time slots*. By interleaving multiple users in the available time slots, increases in the capacity (*i.e.*, number of simultaneous users) of the system can be achieved. At its maximum, the IS-54 standard provides for a factor of 6 increase over the current 30 *KHz* analog (AMPS) standard by packing 6 voice channels into a single TDMA *frame*. However, initial implementations provide for a factor of 3 increase only. TDMA requires substantial modifications to the base station receiver hardware as well as the mobile units themselves, since current analog units are not capable of exploiting this technology. Consequently, a dual-mode standard, supporting both the new digital and the old analog transmission schemes, has had to be adopted.

2.1.2 CDMA

CDMA allows multiple users to share a common frequency channel by using coded modulation schemes. The technology involves preprocessing the signal to be transmitted by digitizing it, modulating a *wideband* coded pulse train, and transmitting the modulated coded sign... in the assigned channel. Multiple users are given distinct codes which decoders in the receivers are programmed to detect. If properly designed, the number of simultaneous users of such a system can be increased over the current state-of-the-art. Proposed systems indicate a potential factor of 10 improvement in spectral efficiency. The SDMA concept described herein can be applied directly to further increase capacity and system performance of CDMA systems by dynamic sector assignment. Practically, increases by factors from four (4) to ten (10) over omnidirectional schemes are achievable with SDMA.

The aforementioned techniques represent various attempts to more efficiently *pack* an increasing number of signals into fixed-width frequency channels. These techniques do not exploit the *spatial* dimension when establishing channels. Common to all the aforementioned systems is essentially omnidirectional (possibly wide-area sectorized) transmission of RF energy in an attempt to establish point-to-point communication links. This turns out to be a reasonable strategy in current systems since the relative locations of the mobile units are not known. It does, however, suffer from an extreme inefficiency in that the ratio of useful power (power actually received by the mobile unit) to the total power transmitted is extremely small. As a consequence, most of the transmitted power from both the base stations and the mobile units is actually interference to the remainder of the system. This RF *pollution* prevents multiple users from sharing the same frequency channel within local areas comprising many cells in all but CDMA transmission schemes where using coding and power control users are allowed to use the same channel.

This document describes how, *in addition* to traditional schemes, the spatial dimension can be exploited to:

1. significantly increase the number of channels that a base station can serve without allocation of more frequency channels,
2. significantly increase the quality of the communication links,
3. significantly reduce the required amount of transmitted power from both the base stations and the mobile units,
4. lower the overall system deployment cost by reducing the number of base stations required to handle a given system load,
5. significantly increase flexibility in system architecture permitting more efficient system deployment,
6. *allow for coexistence with current (e.g., point-to-point) users of the same spectrum!*

This proprietary technology is hereafter referred to as Spatial-Division Multiple Access (SDMA).

2.2 Current Methods for Increasing Capacity and Quality

2.2.1 Microcells

Heretofore, to increase the capacity of cellular systems, the area covered by each base station is reduced, increasing the number of cell sites required to cover a given area, but allowing more users to access the system. The idea is that signals *far enough away* will not interfere with local sources since power dissipates quite rapidly in space the further from the transmitter the receiver is located. This straightforward approach to increasing capacity is often referred to as the *microcellular* concept, and is the currently favored concept for handling anticipated demand in the coming PCSs. SDMA is entirely compatible with the microcellular approach to PCS deployment and in fact will further improve the spectral efficiency, yield an improvement in signal quality, and help to increase the accuracy and reliability of hand-offs.

2.2.2 Sectorization

Sectorization is a currently employed technique in cellular systems for increasing signal quality by dividing up the area served by a base station into sectors. Rather than transmitting omnidirectionally, antennas which transmit the majority of their power in sectors of fixed angular extent (*e.g.*, 120° in a 3-sector system) are used. Multiple fixed antennas cover the entire cell. The advantage of this technique is that by restricting the field of view, the number of cells potentially interfered with is reduced. Since there is insufficient isolation between sectors, channels are not reused in the various sectors in a cell. As a result, capacity is not increased. Thus, fixed sectors can be thought of as simply another technique for reducing the size of the cells in the system to reduce cochannel interference without increasing capacity. Though certainly not a precise statement, SDMA can be viewed as essentially a dynamic (smart) sectorization technique in which the sectors (loosely speaking) *track transmissions from mobile wireless units* and direct energy thereto. However, unlike fixed sectorization schemes, an increase in capacity of the system results as well.

2.3 Cochannel Interference

In current systems, it is assumed that there is only one mobile unit at a time transmitting in a given cell on a given channel. These channels can be frequency channels as in FDMA/TDMA systems, or code channels as in CDMA systems. Other transmitters actively transmitting in the same channel at the same time are considered to be *cochannel interference*, a situation which current systems attempt to prevent since it leads to significant performance degradation. Cochannel interference, in fact, is a major factor in determining how often (spatially) frequency channels can be reused, *i.e.*, assigned to different cells. The cochannel interference problem pervades all wireless communication systems, not just cellular mobile communications, and attempts to solve it in current systems have all been formulated on the premise that the cochannel signals represent disturbances to be eliminated and that only one antenna/receiver output is available for the task.

2.4 Time-domain Equalization

Time-domain adaptive filter techniques have been developed to improve channel quality for digital transmission in the presence of Rayleigh fading which causes intersymbol interference at the receiver. Such *equalization* techniques have been adopted in the current digital GSM and IS-54 cellular systems (D. Goodman, "Trends in Cellular and Cordless Communications," *IEEE Communications Magazine*, June 1991). These techniques are completely compatible with SDMA and can be incorporated in the demodulation step as is currently done in practice. In fact, in many environments characterized by a small number of specular reflections, the equalization problem can be substantially mitigated by appropriately combining the multipath signals arriving from different directions in a process very similar in nature to the concept of *rake filtering* in the time domain.

2.5 Exploiting the Spatial Dimension

The undesirable characteristics of the aforementioned adaptive techniques are a consequence of the fact that only assumed time-domain properties of the received signals are being exploited, and that one of the signals present in the data is treated differently than the remaining signals, *i.e.*, the cochannel interferers. The philosophy adhered to which is unique to SDMA is that cochannel interferers simply represent a plurality of users attempting to access the system simultaneously on the same channel. The fact that SDMA can handle this situation regardless of the modulation type (analog or digital) and in the presence of multiple arrivals of the same signal (*i.e., specular multipath*) is a distinguishing feature over current systems.

Efficient exploitation of the spatial dimension to increase capacity requires the ability to separate a number of users simultaneously communicating on the same channel at the same time in the same local area. This separation is performed as discussed in detail in the next section by distinguishing the signals on the basis of their angle-of-arrival, information which is used to ascertain the location of the mobile transmitters. The process of localization of the mobile transmitters is another distinguishing feature of SDMA over current systems.

Possibly due to the heretofore complex nature of systems containing multiple sensors, wireless communication network designers have eschewed multiple antenna/receiver systems in favor of the simpler single (omnidirectional) receiver. However, with the advent of high-speed general purpose digital signal processors, these complex algorithms are capable of being performed in real-time, making the use of state-of-the-art signal parameter estimation algorithms viable for real-time multiple signal location estimation and cochannel signal separation. Unique to SDMA is the application of these techniques to real-time multiple cochannel source location estimation for improving the capacity and quality of wireless communication networks and, in particular, to PCSs.

3. Detailed Description of SDMA

In this section, a brief overview of current FDMA/TDMA wireless communications systems is presented. Then details of the SDMA system are discussed. Results obtained in processing simulated and real data are presented indicating the efficacy of SDMA in the PCS environment.

3.1 Brief Description of Current Systems

FIG. 3-1 shows the current state-of-the-art in wireless communication networks. Wireless transmitter/receiver units (20,22,24) are assigned to distinct (frequency) channels and thereby allowed to communicate simultaneously. As aforementioned, these *channels* can be frequency channels, time-slots in particular frequency channels, or code channels in a particular frequency channel. A multi-channel receiver (26) exploits the fact that they are on different frequency channels to correctly separate the signals (28,30,32) which are then subsequently demodulated and passed along to the rest of the network. A multi-channel transmitter (40) transmits signals (34,36,38) to the wireless units (20,22,24) in another set of distinct frequencies. For example, in current cellular mobile communication systems, mobile units receive transmissions from base stations in channels 45 *MHz* above those frequency channels they transmit information to the base stations. This allows for simultaneous transmission and reception of information at both the base station and mobile units. It is also possible to use time-multiplexing and voice compression to transmit and receive on the same frequency, however this concept would not be amenable to high-speed continuous data transmission.

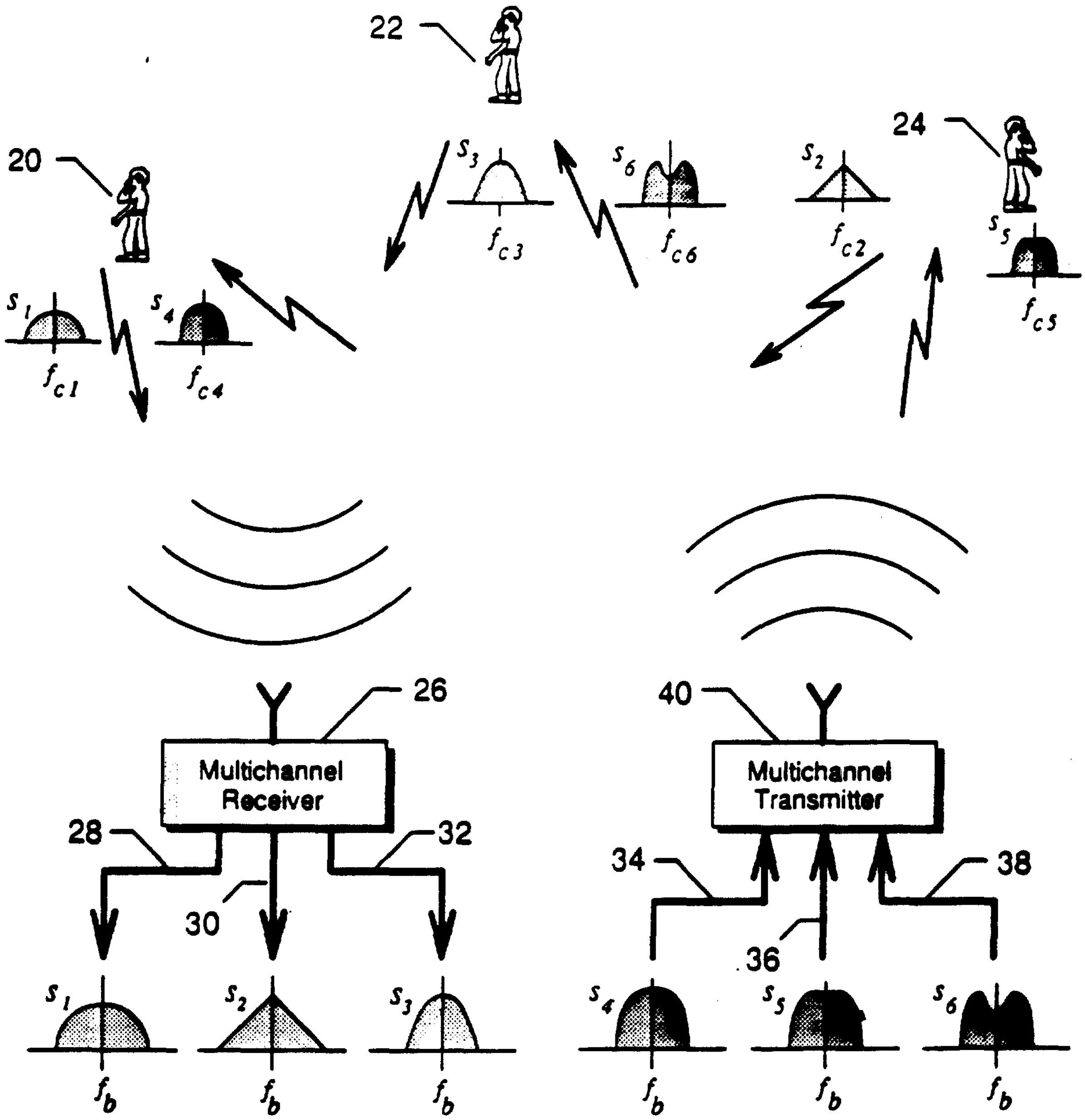

Figure 3-1: Diagram of Current FDMA Systems: Multiple Wireless Units Transmitting on Different Channels at the Same Time

3.1.1 Cochannel Interference and System Limitations

FIG. 3-2 shows a limitation of current wireless communication systems. Wireless units (20,22,24) transmitting on the same conventional channel (the same carrier frequency f_{c1} in this diagram) can not be resolved at the receiver (26) due to the fact that there is no way to distinguish one signal from the other when they share the same channel. The receiver output (28) is a combination of *all* signals present in the channel even after down-conversion to baseband frequency f_b.

FIG. 3-3 shows a similar limitation of current wireless communication systems with respect to communication from the base station transmitter (40) to the remote receivers. The function of the multi-channel transmitter is to up-convert signals from baseband frequency f_b to one of the multi-channel carrier frequencies for transmission to the mobile unit. Wireless units (20,22,24) on a particular channel (the same carrier frequency f_{c1} in this diagram) receive a combination of multiple signals transmitted from the base station transmitter (40) in that frequency channel (34). This is due to the fact that there is no method in the current state-of-the-art for preventing all signals transmitted in the same frequency channel from reaching all receivers in a given cell or sector thereof set to receive signals in that particular channel. Signals received at the wireless units are combinations of all signals transmitted in that channel.

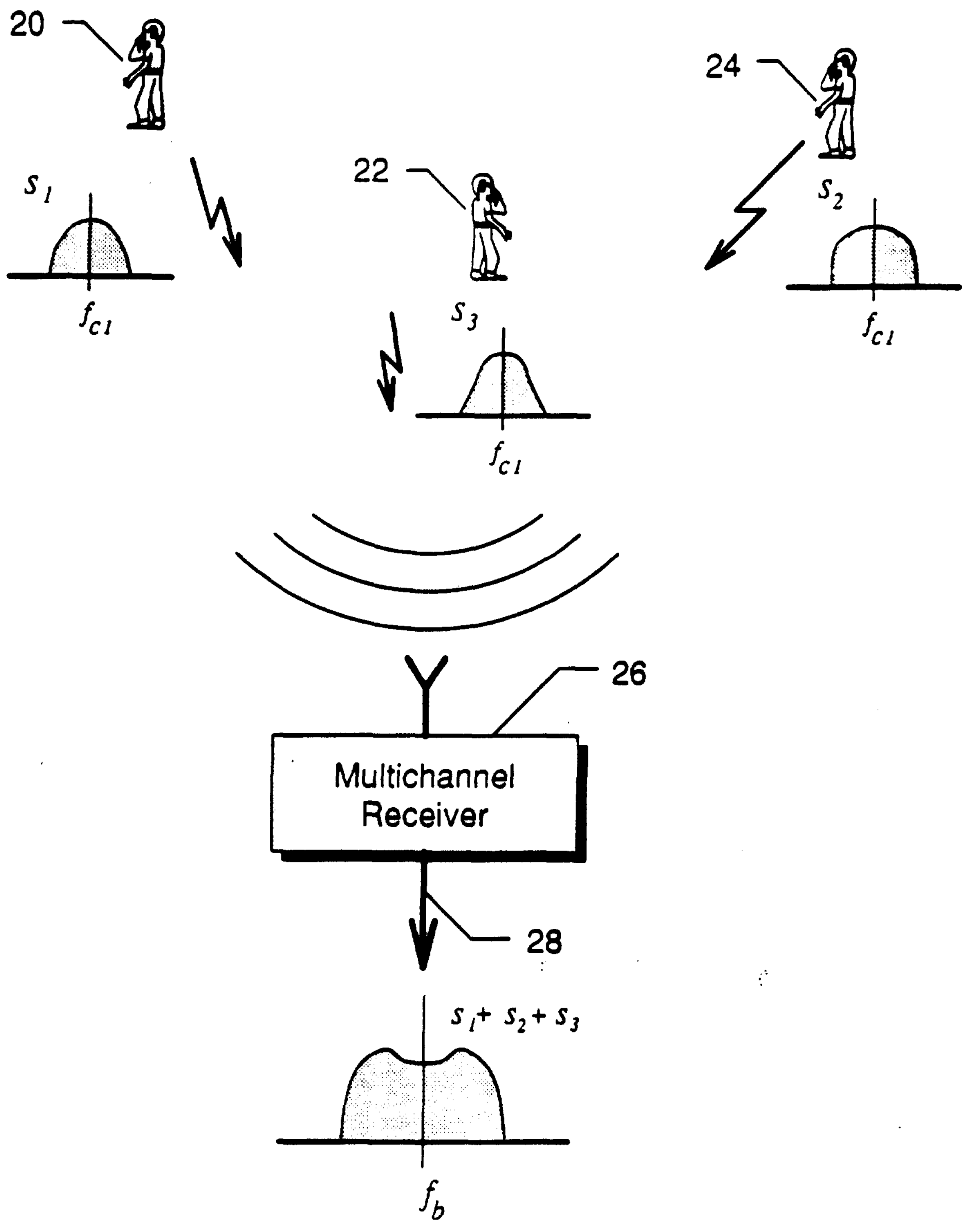

Figure 3-2: Cochannel Interference Resulting from Multiple Wireless Units Transmitting on the Same Channel at the Same Time

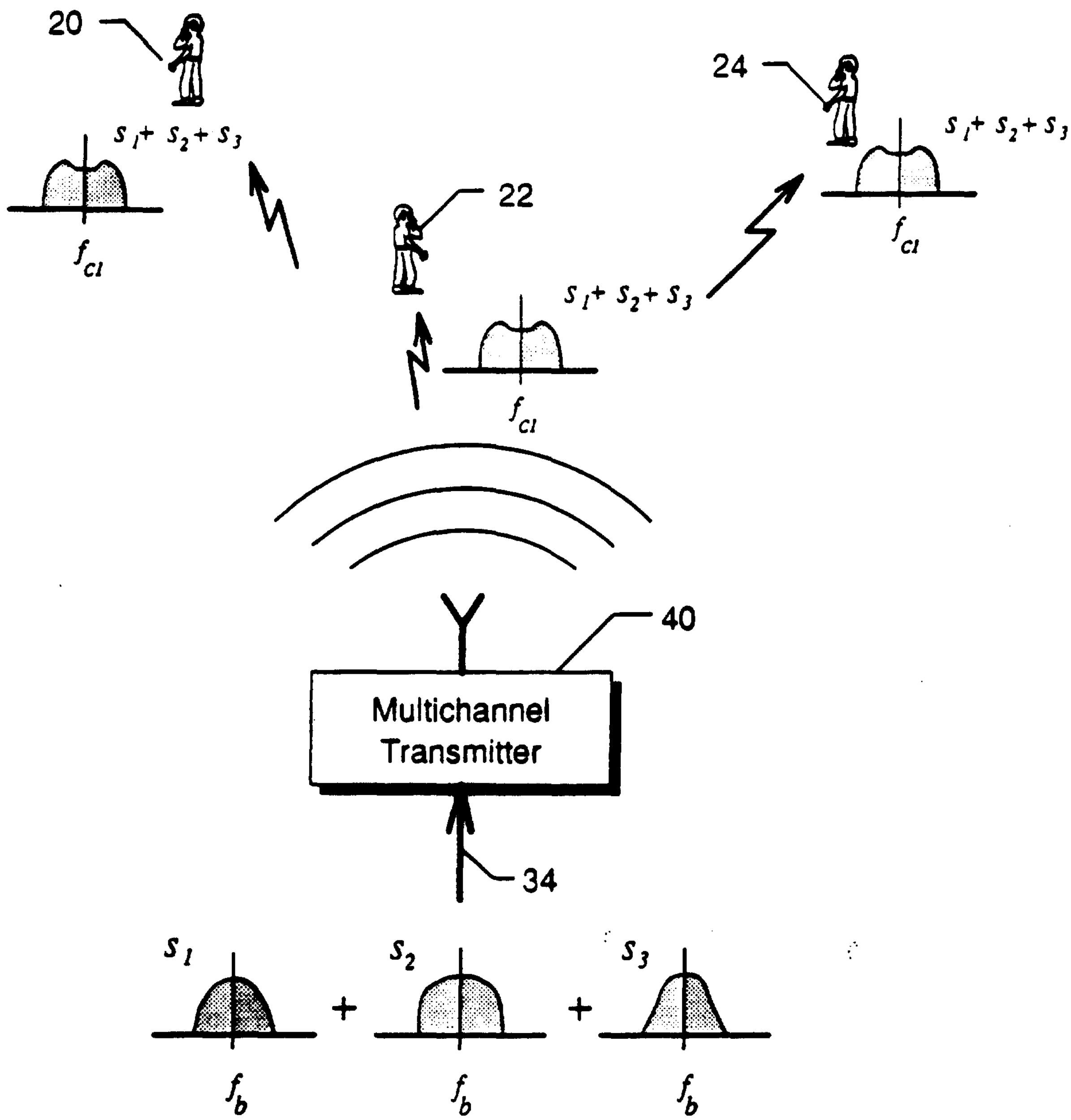

Figure 3-3: Cochannel Interference Resulting from Broadcast Transmission of Multiple Signals on the Same Channel to Multiple Wireless Units at the Same Time

3.2 SDMA

3.2.1 Spatial Demultiplexing for Reception

FIG. 3-4 is an illustration of how SDMA overcomes the aforementioned multiple signal reception problem at one or more base stations. Multiple signals from wireless units (20,22,24) transmitting in the same channel are received by an array of sensors and receivers (42). These *cochannel* signals are spatially demultiplexed by a spatial demultiplexer (46) which is controlled by a Spatial Division Multiple Access signal Processor (SDMAP) (48). The demultiplexed signals (50) are then sent to signal demodulators as is done in current systems.

3.2.2 Spatial Multiplexing for Transmission

FIG. 3-5 is an illustration of how SDMA overcomes the aforementioned multiple signal reception problem at the mobile wireless unit. Multiple signals (64) from signal modulators, assumed therein as all being in the same frequency channel for illustrative purposes, are appropriately combined by a spatial multiplexer (66) under control of the SDMAP (48) so as to eliminate all cochannel interference at the wireless units (20,22,24). These signals (68) are sent to multichannel transmitters (70) and subsequently transmitted by an array of antennas to wireless units (20,22,24). As indicated in the illustration, by appropriate design of the spatial multiplexer using Spatial Communications, Inc. proprietary algorithms, wireless unit (20) receives none of the signal being transmitted to units (22) or (24), and similarly for the other two units. In conjunction with FIG. 3-4, multiple full-duplex links are hereby established.

FIG. 3-6 shows a block diagram of an SDMA system successfully receiving multiple signals in one channel and transmitting multiple signals in another channel by using different spatial channels. The intent of the figure is to indicate that these messages are broadcast on the same (frequency) channels, from the wireless units to the base-station at f_{c1} and from the base station to the wireless units at f_{c2}, at the same time. This is a situation heretofore not allowed in current FDMA and TDMA systems since the messages *interfere* with each other as indicated in FIG. 3-2 and FIG. 3-3. Signals transmitted in the same channel by wireless units (20,22,24) are received at the base station by multiple antennas. The output of each of m_r antennas is sent to a *multichannel receiver* as is currently done in single antenna systems.

3.2.3 Description of the SDMA System

The multichannel receiver takes an antenna input and has one output for each frequency channel which it is capable of processing. For example, in proposed PCS systems,

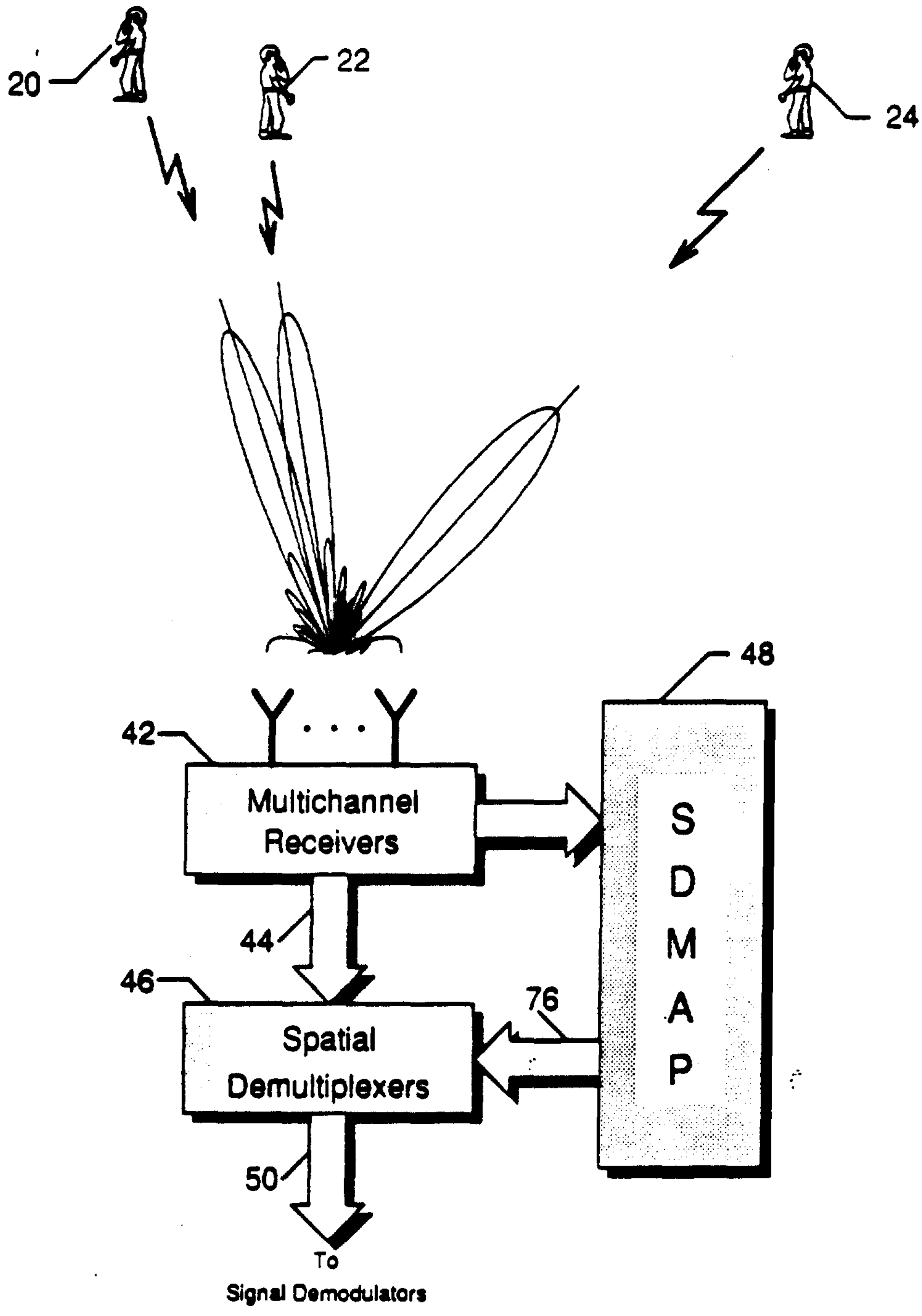

Figure 3-4: Multiple Cochannel Signal Reception at the Base Station Using SDMA

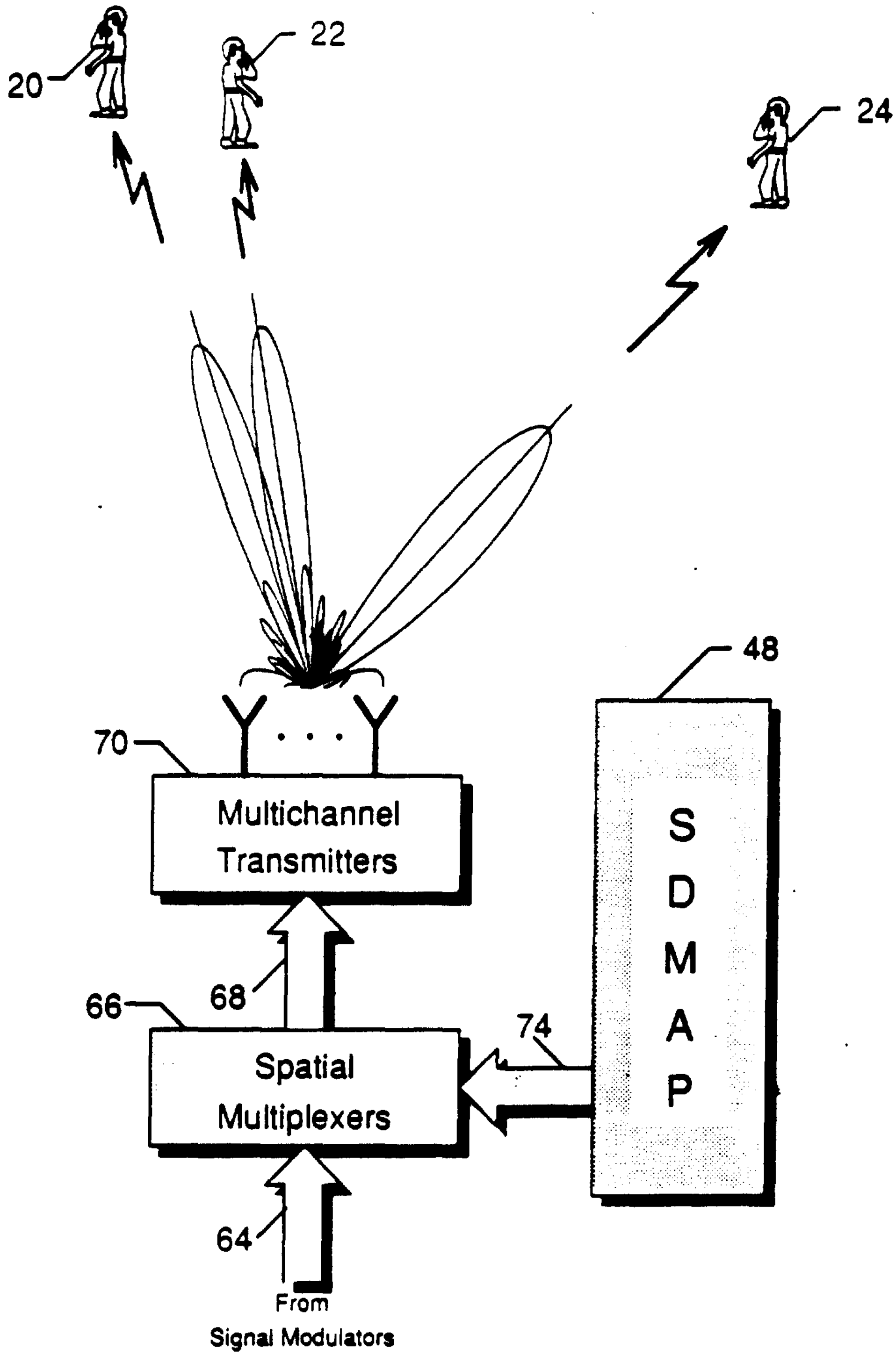

Figure 3-5: Multiple Cochannel Signal Transmission from a Base Station Using SDMA

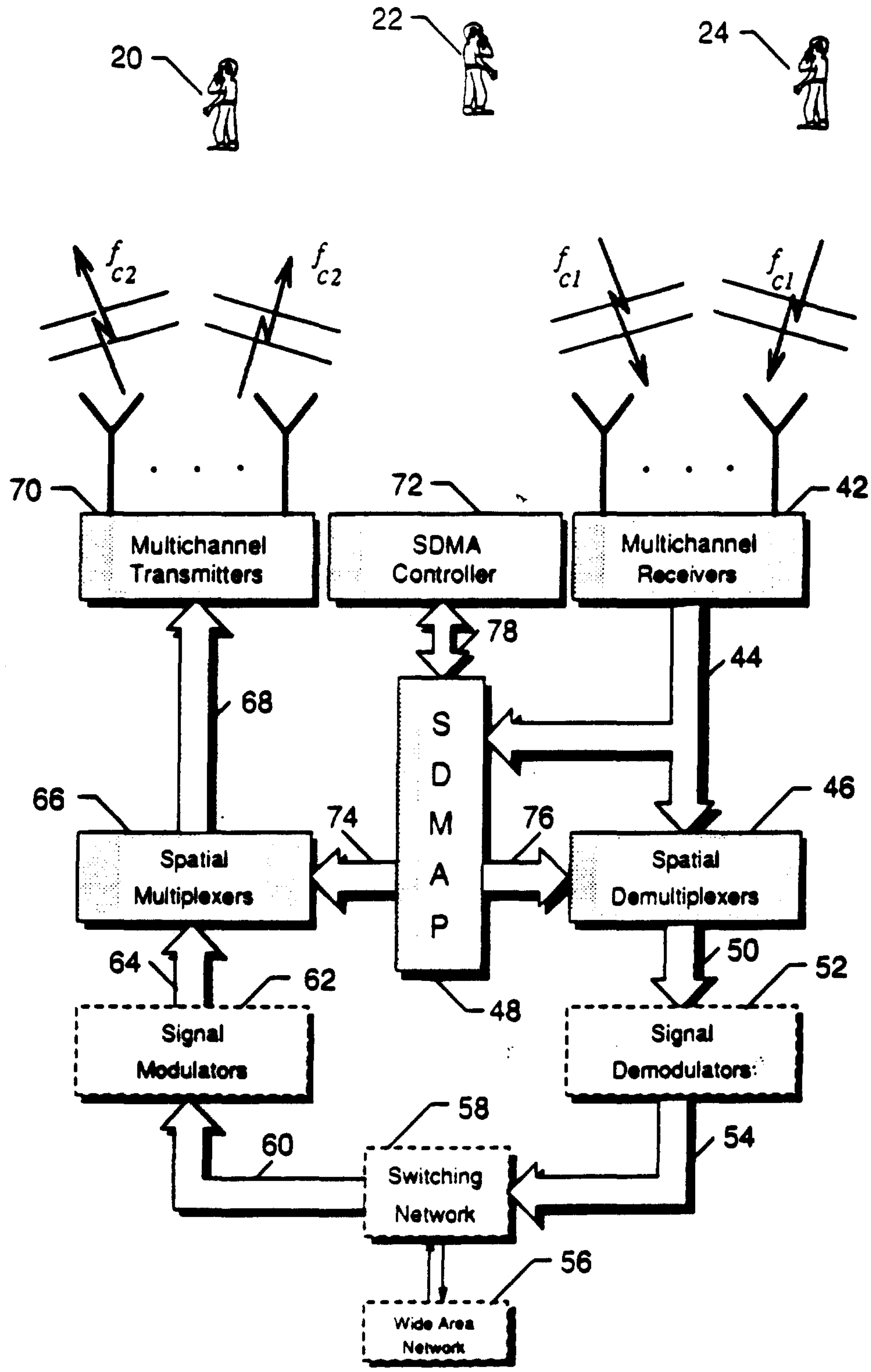

Figure 3-6: Block Diagram of the SDMA System Receiving and Transmitting Multiple Signals in A Single Channel

the receiver consists of a bank of bandpass filters, one such filter tuned to each of the frequency channels assigned to that base station. One such receiver can be assigned to each antenna as shown in FIG. 3-7 (102,104,106), or several antennas can be switched via a high-speed switching circuit to a single receiver. The outputs of the multichannel receivers for a particular (frequency) channel are multiple signals (112,114,116), one signal from that channel for each antenna/receiver pair. These signals are processed as a group by the SDMAP/Spatial Demultiplexer (120) so as to recover the original transmitted signals (122,124,126). Though the diagram implies that a single SDMAP and spatial demultiplexer is dedicated to each channel, several channels can be multiplexed onto a single SDMAP and spatial demodulator depending on processor speed.

Referring back to FIG. 3-6, receiver outputs (44) are digitized after down-conversion to baseband in the multichannel receivers (42) and transmitted in digital form to SDMAPs (48) and spatial multiplexers (46). The outputs of the spatial demultiplexers (50) are demodulated then sent to the switching network (58).

Generally, a function of the SDMAP (48) is to calculate appropriate control signals for the spatial demultiplexer (46) and spatial multiplexer (66) by processing the information received from the receivers (42) and information provided by the SDMA controller (78). The SDMAP also sends tracking and other signal parameter information to the SDMA controller (72) for use in channel assignment and intelligent hand-off. These processes are performed using state-of-the-art signal processing software which implement, among others, recently developed high-resolution direction finding, signal copy, and robust transmission algorithms which are the proprietary property of Spatial Communications, Inc. A detailed description of the SDMAP is given below.

3.2.3.1 Multichannel Receivers

Spatial demultiplexers (46 in FIG. 3-6) demultiplex the outputs (44) of the multichannel receivers (42). This function is performed for each (frequency) receive channel assigned to the base station. In each channel, the signals (44) are appropriately combined by the spatial demultiplexer to provide one output for each signal present in that channel (C1 in FIG. 3-7). Herein, *appropriately combined* means combined so that the signal from each wireless unit in a channel appears at the appropriate output of the spatial demultiplexer. This is possible because to each wireless unit, electromagnetic propagation and reception effectively assigns a unique *spatial code*, and the SDMAP is the spatial *decoder*. The outputs (50) of the spatial demultiplexer (46 in FIG. 3-6) for a particular channel are the separated signals transmitted from the wireless units to the base station in that channel, and are demodulated as is done currently are then routed through a switching network (58) to their appropriate destination. Signals destined for the wireless units are

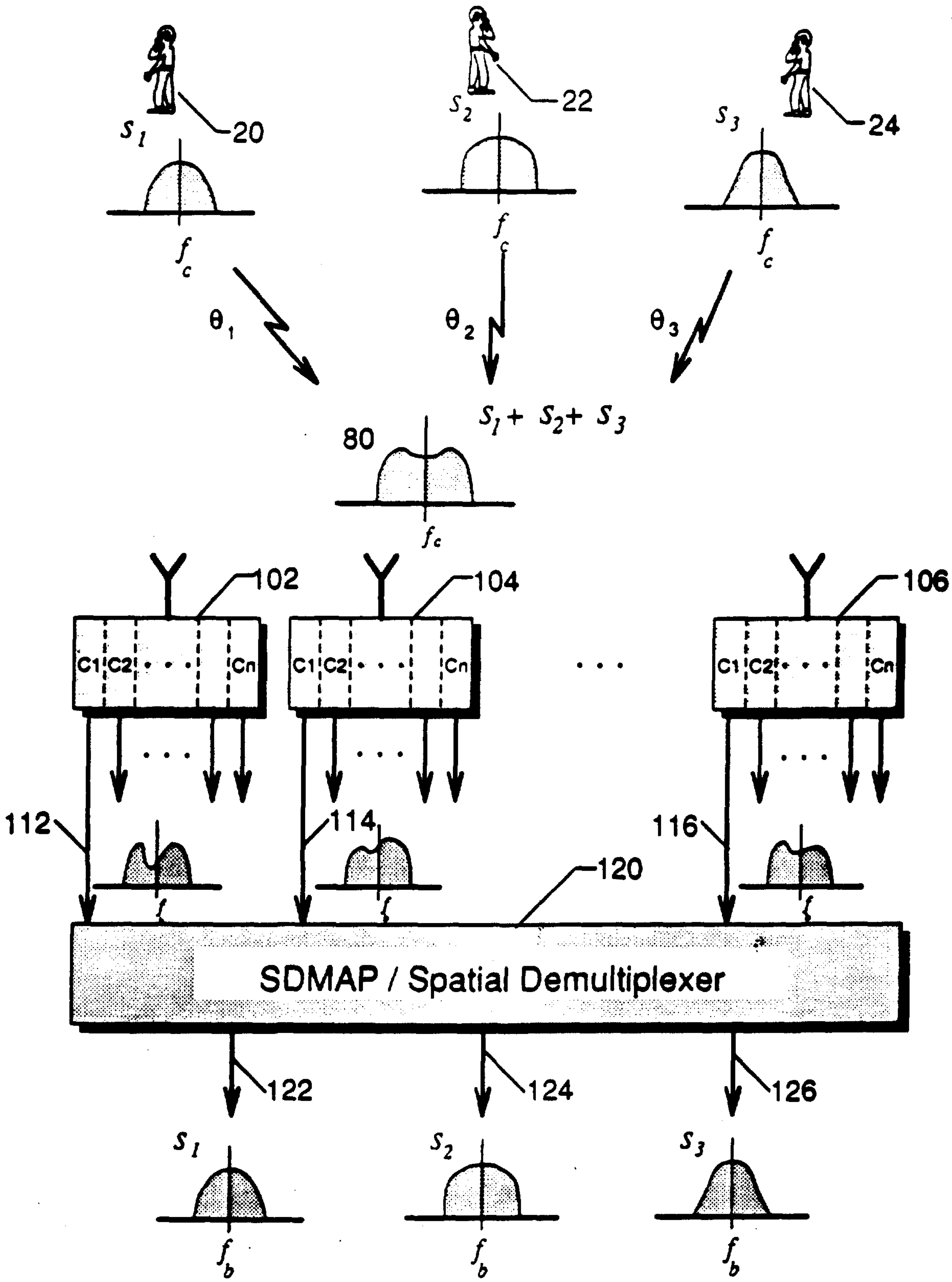

Figure 3-7: Breakdown of the SDMA Multi-Channel Base Station Receiver

obtained from the same switching network (58) and directed to signal modulators (62). Modulated baseband signals (64) are sent to spatial multiplexers (66) where they are appropriately processed as directed by the SDMAP (48) for transmission to the wireless units. In this illustration (FIG. 3-6), these wireless units are assumed to be the same as those whose signals were received in the receivers (42).

3.2.3.2 Multichannel Transmitters

Multichannel transmitters (70) similar in structure to the receivers (42) are employed, there being one transmitter for each of the m_{t_x} transmitting antennas as shown in FIG. 3-8 (152,154,156). Each transmitter appropriately combines the outputs of each channel assigned to the base station for the purpose of transmission of the signals through the associated antenna to the wireless units.

The function of the spatial multiplexer (66) shown in FIG. 3-8 is to multiplex one or more signals (64) into a particular channel (C1 in FIG. 3-8), but *different* spatial channels. The spatial multiplexer (66) appropriately combines the signals (64) and provides one output for the particular channel (C1 in FIG. 3-8) in each transmitter (40). Herein, *appropriately combined* means combined so that each wireless unit receives only the signal intended for it. No other signals arrive at that particular wireless unit receiving in that (frequency) channel. This is a unique aspect of SDMA.

Spatial multiplexing is performed for each channel (C1, C2, ..., Cn in FIG. 3-8). A separate spatial multiplexer can be used for each channel, or the multiplexing task for several channels can be performed by the same multiplexer hardware. The signals (62) are digitized if necessary, appropriately combined in the spatial multiplexer, then sent to the transmitters for D/A conversion and transmission to the wireless units.

3.2.3.3 The Spatial Division Multiple Access Signal Processor (SDMAP)

FIG. 3-9 shows a breakdown of a Spatial Division Multiple Access signal Processor (SDMAP) (48). The function of the SDMAP includes determining how many signals are present in a particular channel, estimating signal parameters such as the spatial location of the transmitters (*i.e.*, directions-of-arrival DOAs and distance from the base station), and determining the appropriate spatial demultiplexing and multiplexing schemes. Inputs (44) to the SDMAP include outputs of base station receivers, one for each receiving antenna. The receivers perform *quadrature detection* of the signals, providing *in-phase* (I) and *quadrature* (Q) components (signals) output from each channel behind each antenna. The receivers can digitize the data before passing it to the SDMAP, or digitization can be performed in the data compressor (160) as aforementioned.

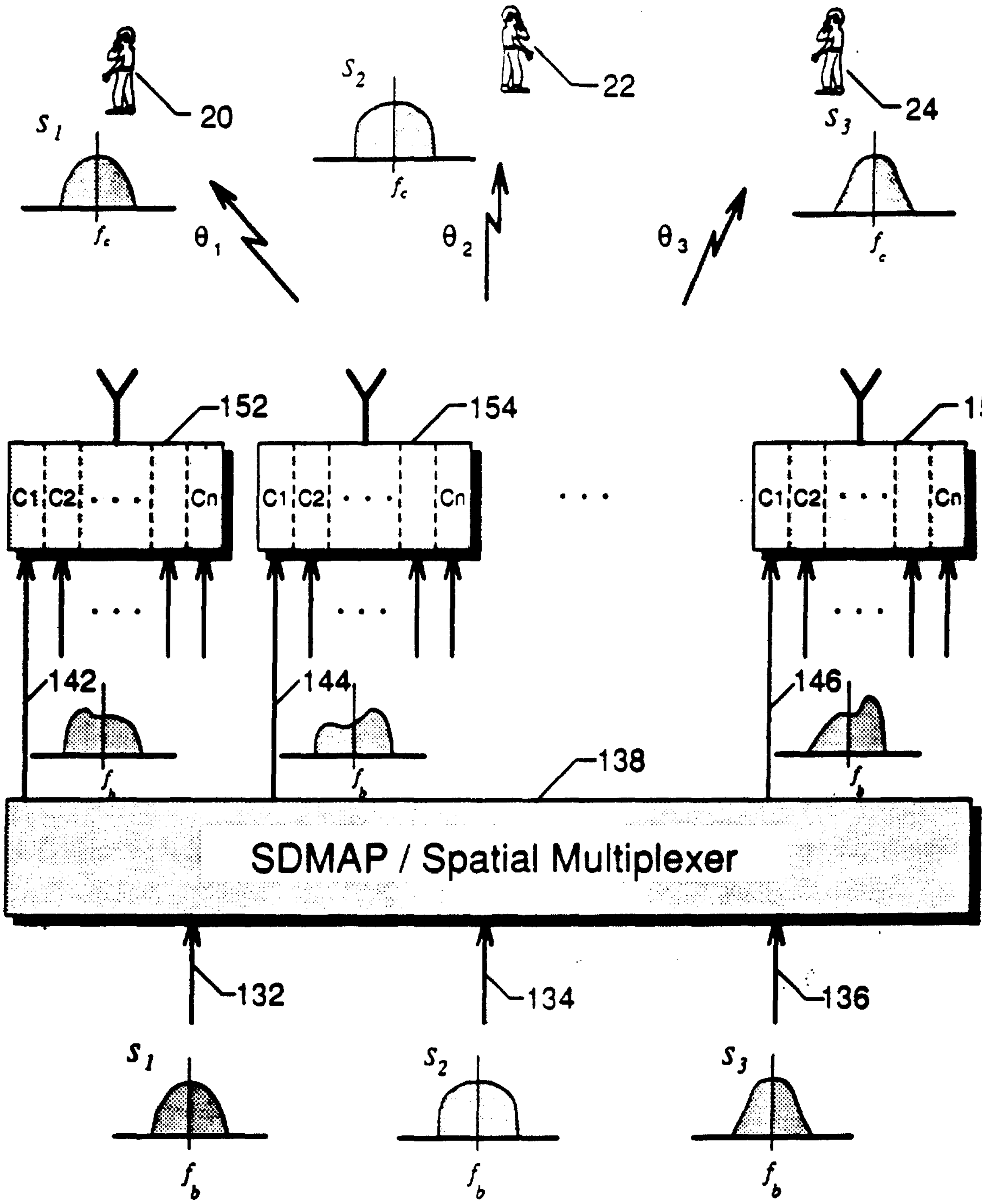

Figure 3-8: Breakdown of the SDMA Multi-Channel Base Station Transmitter

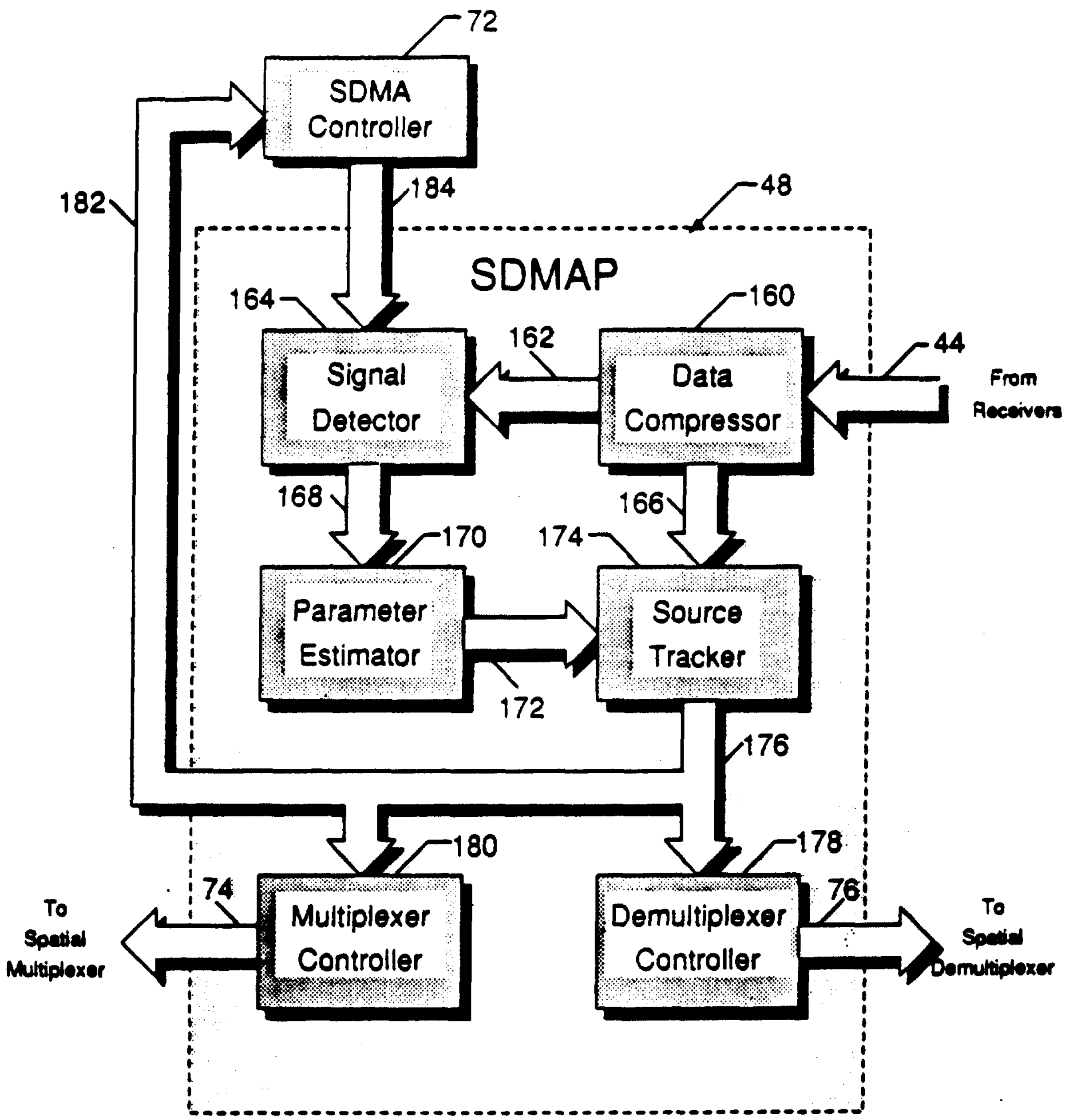

Figure 3-9: Breakdown of the Spatial Division Multiple Access Signal Processor (SDMAP)

In relatively clean RF environments, the SDMAP accomplishes its task by first obtaining estimates of important signal related parameters such as their directions-of-arrival (DOAs) without exploiting temporal properties of the signal. In more complex RF environments such as building interiors, the known training sequences placed in the digital data streams for the purpose of channel equalization are used in conjunction with sensor array information to calculate signal parameter estimates such as DOAs and signal power levels. This information is then used to calculate appropriate *weights* (76) for a spatial demultiplexer implemented as a linear combiner, *i.e.*, a weight-and-sum operation. Time-of-arrival (TOA) related parameters from the parameter estimator are used in conjunction with signal correlation parameters to ascertain which signals are multipath versions of a common signal. Relative delays are then calculated such that the signals can be *coherently combined*, thus further increasing the quality of the estimated signals. The ability to exploit sensor array information in this manner is unique to SDMA.

The function of the spatial demultiplexer can also be performed in conjunction with the estimation of other source parameters such as the DOAs. As an example, the (nearly) constant modulus property (*i.e.*, constant amplitude) of various communication signals such as digital phase-shift-keyed (PSK) and analog FM waveforms can be exploited along with properties of the array of receiving antennas to simultaneously estimate the source waveforms as well as their DOAs. Here, the function of the spatial demultiplexer (46) is assumed in the SDMAP (48), and the outputs of the SDMAP (76) are the spatially demultiplexed signals to be sent to the demodulators.

Referring again to FIG. 3-9, data compression (160) is performed to reduce the amount of data, and can consist of accumulation of a sample covariance matrix involving sums of outer products of the sampled receiver outputs in a particular channel. Hereafter, these sampled outputs are referred to as *data vectors*, and there is one such data vector at each sample time for each of the channels assigned to a particular base station. The compressed data can also be simply the unprocessed data vectors. If I and Q signals (44) are output from the receivers, each data vector is a collection of m_r complex numbers, one for each of the m_r receiver/antenna pairs.

Compressed data (162) are passed to a signal detector (164) for detection of the number of signals present in the channel. Statistical detection schemes are employed in conjunction with information from a SDMA controller (72) to estimate the number of sources present in the channel in this time interval. This information and the (compressed) data (168) are sent to a parameter estimator (170) where estimates of signal parameters including those related to the source locations (*e.g.*, DOAs and range) are obtained.

In simple RF environments, location-related parameter estimates (172) are passed to a source tracker (174). The function of the source tracker is to keep track of the positions of each of the transmitters as a function of time. This is implemented by state-of-the-art nonlinear filtering techniques such as extended Kalman filters (EKFs). Inputs to the EKF embodiment include the DOAs and TOAs from the local base station. DOA and TOA measurements from other nearby cell sites also receiving transmissions from the mobile units can be incorporated as well along with known locations of the base stations to further improve the estimation accuracy of the EKF. The tracker (174) outputs are sent along with the (compressed) data (176) to a spatial demultiplexer controller (178), to control the function of the spatial demultiplexer, and to a spatial multiplexer controller (180) to control the function of the spatial multiplexer.

3.2.4 The SDMA Controller

FIG. 3-10 displays a SDMA controller (72) which supervises channel allocation, and a plurality of SDMA systems (202,204,206). As aforementioned, each SDMA system receives signals (44a,44b,44c) from the multichannel receivers (42) and sends signals (68a,68b,68c) to the multichannel transmitters (70) for transmission to the wireless units. The SDMA systems also communicate (tracking) information (182a,182b,182c) as aforementioned to the SDMA controller and receive information (182a,182b,182c) from the SDMA controller. Not shown in this illustration is the link between the base stations and their access to the wide area network through a switching network.

The function of the SDMA system is performed for each channel (202,204,206), denoted CH 1, CH 2, ..., CH n in FIG. 3-10, allocated to a base station for reception. There can be a separate SDMA system for each channel, or several channels can be processed in the same SDMA system depending on system load and processor speed.

An objective of the SDMA controller (72) is to prevent wireless units from becoming coincident in (frequency or code) channel, time, and spatial (location) space. As required, the controller instructs the wireless units to change to different (frequency or code) channels via standard messaging schemes.

SDMA controllers at various base stations (190,194,200) can also send tracking and frequency allocation information, in addition to other relevant source parameters such as signal power, concerning all the wireless units in their cell (192,196,198) to a base station supervisor (220). This information can be used to simplify hand-off procedures employed in current systems. With knowledge of the locations and velocities of all the transmitters and knowledge of the areas covered by each of the base stations, efficient and reliable hand-off strategies can be implemented.

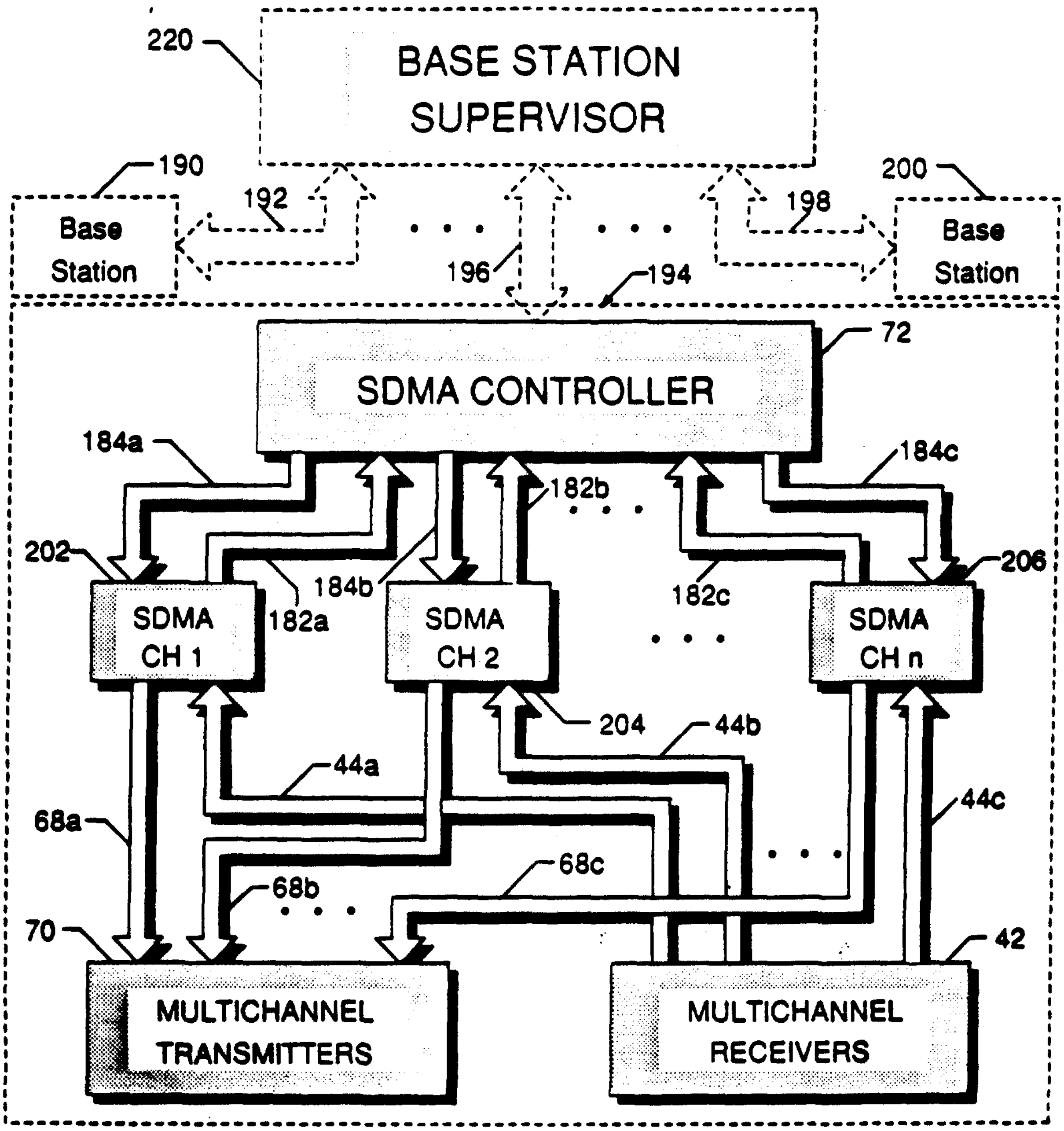

Figure 3-10: Breakdown of Multiple SDMA Processors Increasing Base Station Capacity

The function of the SDMA controller can also include relaying to each base station the locations and channel assignments of transmitters in neighboring cells. This information can be used in the spatial multiplexer and demultiplexer controllers in the SDMAP to improve the performance of the spatial multiplexers and demultiplexers. Further improvements in capacity are also realized herein by allowing dynamic allocation of receive and transmit channels among the various cell sites and mobile units. The ability to track multiple transmitters in wireless communication networks and the significant improvements made with regard to system capacity and quality are unique to SDMA.

4. Benefits of SDMA

SDMA addresses the key issues and problems facing the PCS industry as well as other wireless communication networks by essentially restoring the property of wireline service, that of point-to-point communication, lost when wires are eliminated in favor of wide-area (omnidirectional) transmission and reception of (electromagnetic) radiation. No attempt is made in current systems to:

1. exploit information collected by an array of sensors for the purpose of detecting and estimating the location of multiple signals on the same (frequency) channel at the same time,

2. simultaneously estimate all transmitted signals, or

3. use spatial information to simultaneously selectively transmit different signals to one or more users on the same (frequency) channel.

These are unique to SDMA and can significantly improve the capacity and quality of PCSs. As discussed in detail in Section 6, the cost associated with this improvement is the increase in hardware complexity per base station required. The overall system costs per user can be reduced, however, since more users are allowed, and fewer base stations are required.

The benefits of SDMA include:

1. allowing simultaneous use of any conventional (frequency, time-slot, or code) channel by multiple users, none of which occupy the same location in space, thereby increasing the capacity (*i.e., spectral efficiency*) of current PCS wireless information networks,

2. tracking of mobile sources, mitigating hand-off and signal mangement problems present inherent in current mobile cellular communication systems,

3. transmitter position determination, enabling location-related services to be provided,

4. independence of the particular signal modulation type and therefore compatibility with current and future modulation schemes in wireless communication systems,

5. improved signal quality at both transmitters and receivers,

6. a certain amount of communication security by transmitting signals only in preferred directions thereby limiting the amount of unintentional radiation,

7. allowing a decrease in transmitter power to be effected at the base station by directive transmission while still improving signal quality by increasing amount of power received by the mobile unit,

8. decrease in signal degradation due to cochannel interference thereby allowing frequencies in adjacent cells to be re-used more frequently, further increasing system capacity,

9. providing capability for the new PCS systems to coexist with other primary users of the same bands (*e.g.*, point-to-point microwave) without having to require modifications of any of the other existing system operations.

In the case of FDMA/TDMA systems similar to the proposed IS-54 digital cellular system, the increase in spectral efficiency is effected by allowing multiple users to occupy the same frequency channels and the same time slot as long as they are not at the same location (angular position) relative to the local base station. The number of such simultaneous users is theoretically limited to the number of elements in the receive array less one, however practically for robustness considerations the number should be limited to on the order of 50% to 70% of the number of elements. Thus, a six element receive array of omni-directional antennas can practically track four (4) mobile transmitters providing a factor of four (4) increase in capacity. As aforementioned, further increases in spectral efficiency can be realized by increasing the number of antennas. A practical upper limit of approximately a factor of ten (10) over omnidirectional base stations is anticipated given the present state of DSP technology and the complexity of the RF environments to be encountered. In summary, increases in spectral efficiency of factors from 2 to 10, dependent upon the system parameters required, are achievable in the present state-of-the-art for FDMA/TDMA systems. Base stations can be designed to meet expected demand while minimizing hardware costs by designing with the appropriate number of antennas. When necessary, the spectral efficiency can be increased (up to a factor of 10) by adding more antennas. Though the technical approach is different, similar capacity increases can be realized for CDMA systems where many users share the same frequency band, but use different *temporal codes*.

The ability to establish full-duplex links requires the transmit array have at least as many elements as cochannel mobile units. Practically, as mentioned previously, 50% to 100% more antennas than mobile units provides a degree of robustness to system errors and is recommended. When appropriately placed, more transmit antennas can be used to further reduce power consumption and RF pollution by confining the transmitted energy to smaller angular sectors. Mathematically, the power transmitted in each of M_{tx} transmit antennas can be reduced be a factor of M_{tx}^2 yielding an overall power reduction of a factor of M_{tx} while delivering the same amount of power to the mobile units.

The ability to directionally transmit can also be used to increase the effective coverage area of each cell, trading total transmitter power for cell radius. Thus, if the total transmitter power is held constant and a 1/3-power law is assumed for RF attenuation, the cell radius can be increased by $M^{1/3}$ leading to the requirement for fewer base stations.

An important benefit of SDMA implementation in the PCS environment is the ability to coexist with current users of the proposed PCS spectrum (901-9600 *MHz*, 1800-2200 *MHz*). There are a significant number of microwave users currently occupying at least one of the bands (*i.e.*, 1850-1990 *MHz*) proposed for the next generation PCS. The cost of relocation of these users could be substantial. With SDMA, it is possible for established microwave users to coexist with the new PCS users with extremely small *exclusion zones* since the PCS system can be designed (base stations appropriately located) so that complete area coverage is provided without illuminating the microwave antennas (thereby interfering with the current users) from the base stations. Furthermore, since the PCS handsets can operate at lower power than without SDMA, they will contribute proportionately less RF *pollution*.

The ability of the SDMA system to locate and track transmitters also provides several immediate benefits. This ability can be directly used to mitigate the problems associated with cellular-type communication systems when users move from cell to cell. Without knowledge of the relative location of the transmitter, assigning of the transmitter to the appropriate base station becomes a problem. However, when the location of the transmitter is known, assignment is a trivial task. Furthermore, knowledge of the transmitter location enables PCS operators to provide a host of position-related services which other proposed systems can not provide. A unique and valuable element of security (being able to locate a child in distress, *etc.*.) is also provided when the transmitter location is known.